System size dependence of J/ψ production at RHIC

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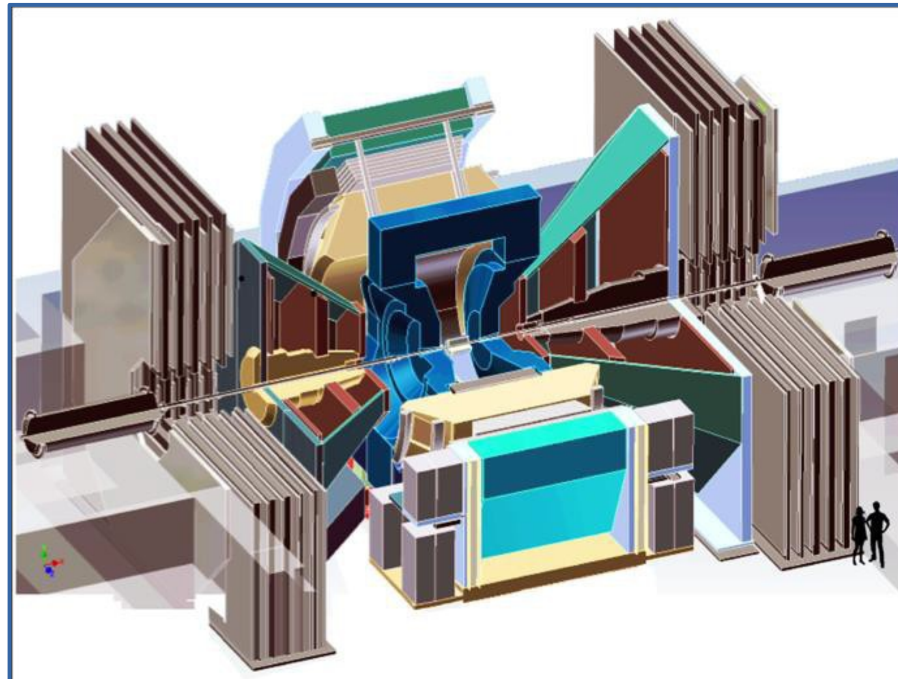
Nuclear Matter Effects
and collision system size

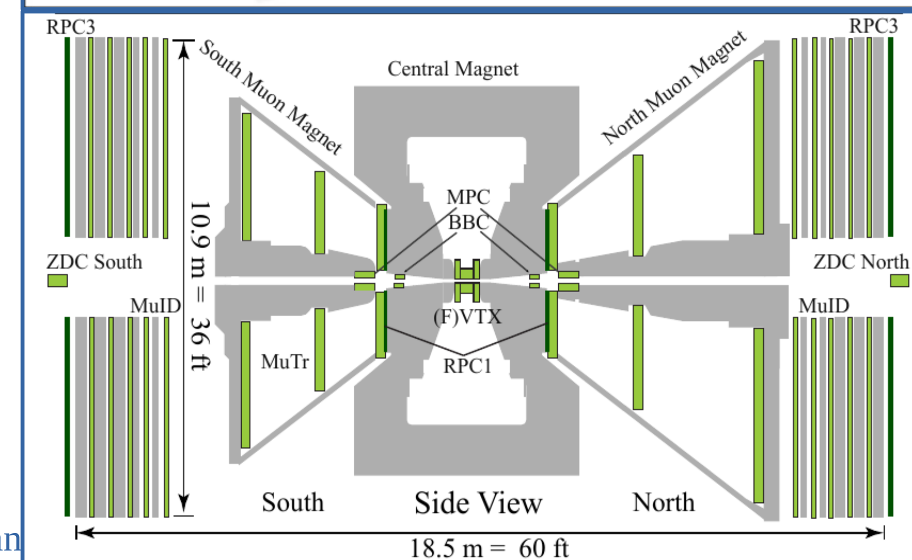
- Phenix has good capabilities to measure J/ψ and probe quarkonia deconfinement and other mechanisms which modify its production
- Two main sources
  - Cold Nuclear Matter effects (CNM)
    - Due to the nuclear target (systems like d+Au)
  - Hot Nuclear Matter effects (HNM)
    - Modification in the created QGP
- Strategy: use different collision systems
  - Measure (then parametrize) CNM effects in p(d)+A
  - A+A collisions will have both CNM+HNM effects
    - "Remove" CNM effects
    - Learn about QGP mechanisms which modify charmonium in different heavy ion systems

Phenix Detector

- **Central arms:** focus on electrons
  - J/ψ, ψ', $\Upsilon \rightarrow e^{+}+e^{-}$, single $e^{\pm}$
  - $|y|<0.35$, $\Delta\phi = \pi$
  - EM Calorimeter, RICH
  - VTX → flavor separation (2011+ Upgrade)
- **Forward arms:** focus on muons
  - J/ψ, ψ', $\Upsilon \rightarrow \mu^{+}+\mu^{-}$, single $\mu^{\pm}$
  - $1.2<|y|<2.2$, $\Delta\phi = 2\pi$
  - Muon Tracker/ID
  - FVTX → flavor separation (2012+ Upgrade)

- Broad contribution to the world's J/ψ measurements:
  - Large energy range: $\sqrt{S_{NN}}$ = 39 – 200 GeV
  - Collision species: p+p, d+Au, Cu+Cu, Au+Au, U+U, (new) He+Au, p+Au, p+Al

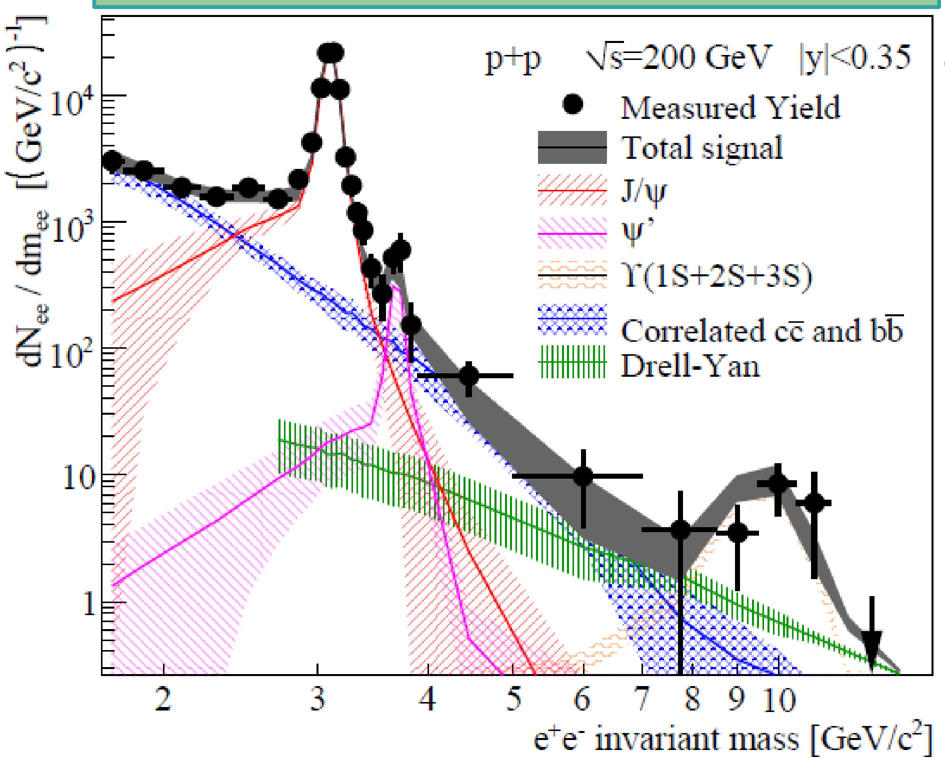




Measuring J/ψ in Phenix

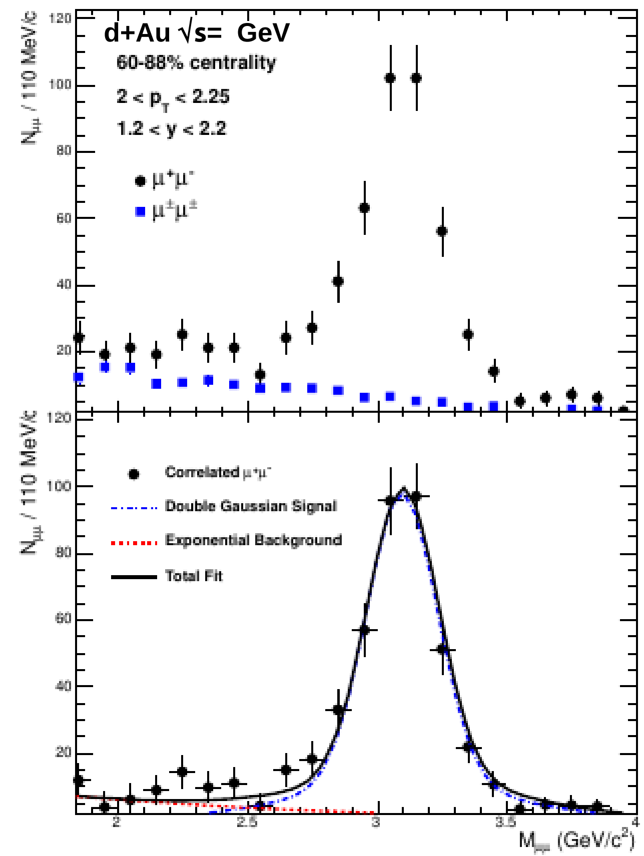
- Calculate the invariant mass from decay leptons

Central arms



Phys. Rev. C. 91 024913 (2015)

Forward arms

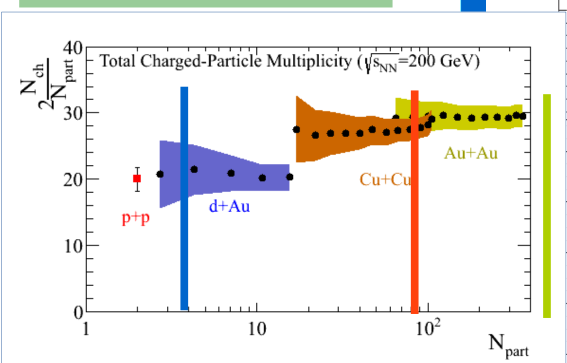


Phys. Rev. C 87, 034904

Measuring J/ψ in Phenix

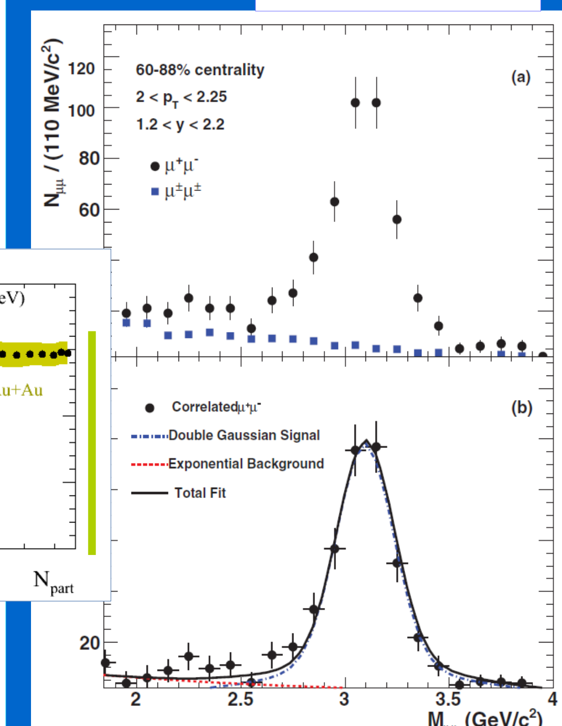
- Challenges at high multiplicity → high background

Total Multiplicity

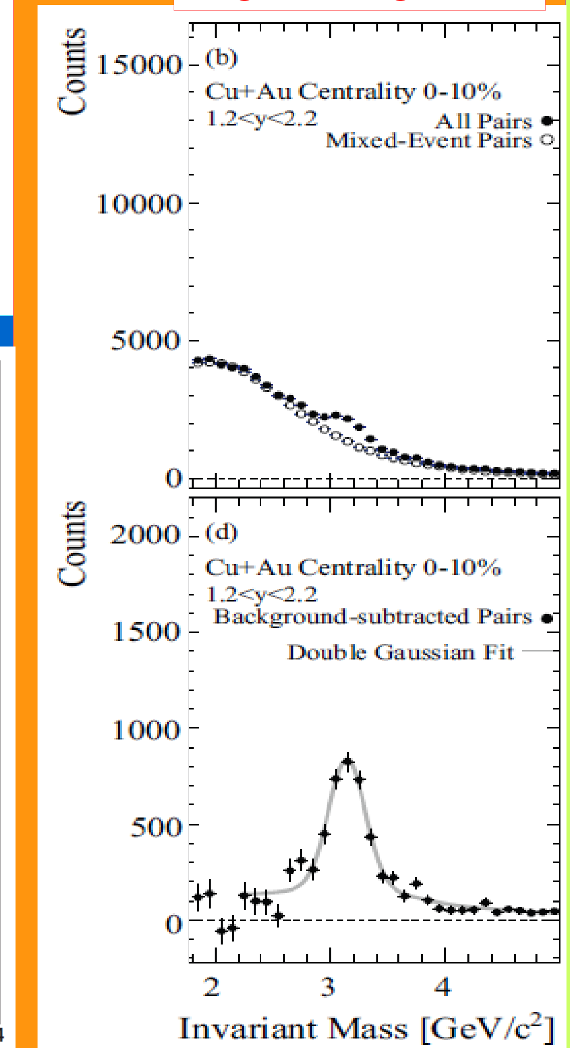


Phys. Rev. C 83, 024913 (2011)

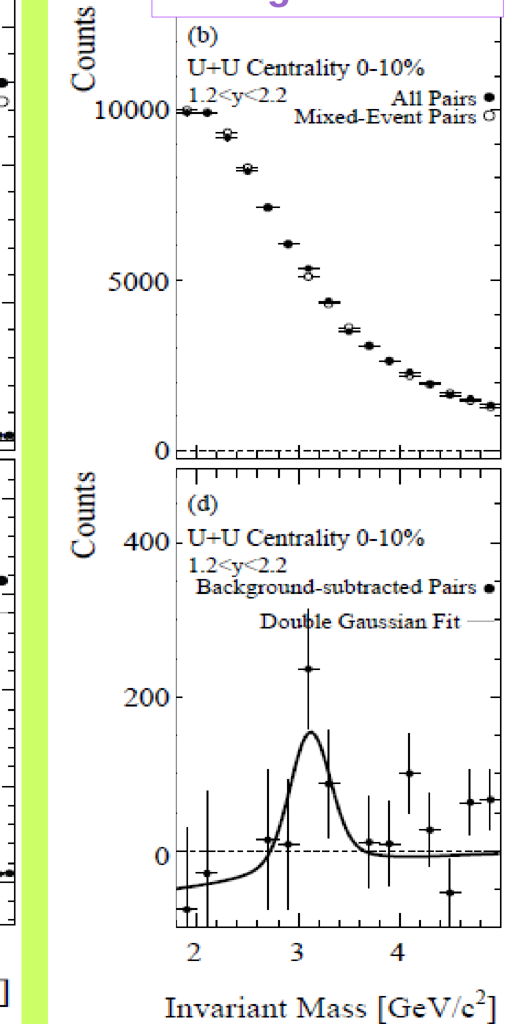
d+Au:
Very Low Background



Central Cu+Au
High Background



Central U+U:
Very High Background



J/ψ nuclear modification

- Competing effects from COLD and HOT nuclear matter
  - Complex admixture of different mechanisms
  - Dependent on kinematics
- Experimentally, separation not clearly established

Gluon shadowing / antishadowing

Parton energy losss in cold matter

Nuclear transverse momentum broadening

cc-bar breakup in the target nucleus

Gluon saturation

destruction

Color screening

Dynamical destruction "melting"

formation

Recombination

Coalescence

property change

Transverse momentum broadening

collective flow

Experimental control parameters

- Control the properties of the created state
  - Each parameter → probes different admixture of nuclear modification

Centrality

Suppression vs path length

System Size/
Collision Asymmetry

Change the relative contributions
of ***Cold*** and ***Hot*** nuclear matter

Rapidity

Probes different gluon
(anti)shadowing

Momentum

Hard collision dynamics

Collision Energy

Change system energy density

Particle Species

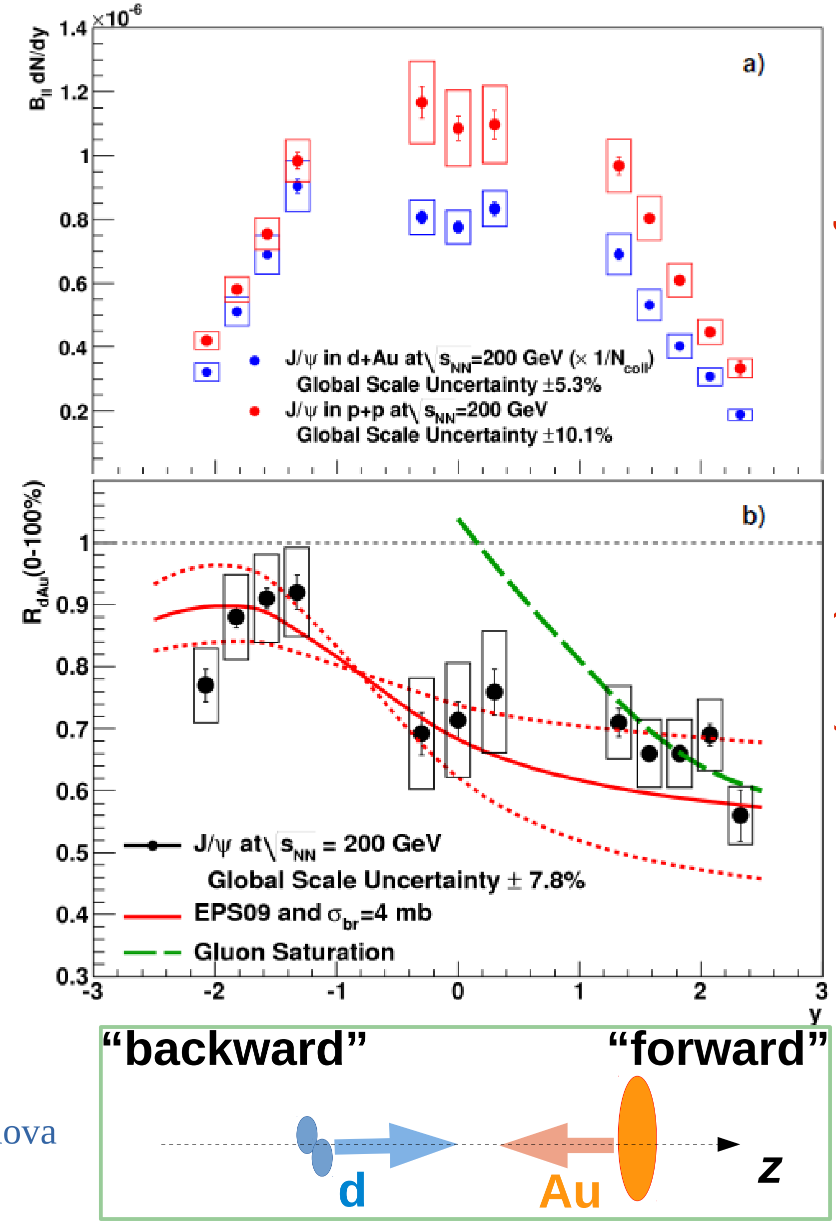
Break-up, Temperature?

Revisited Strategy: Increase variety of collisions-systems to “control” the magnitude of physics effects

Measurements in cold systems

J/ψ in d+Au

- d+Au → nuclear/COLD effect baseline, asymmetric
- d+Au compared to the production cross section baseline in p+p
  - Forward/backward asymmetry
  - More suppression at forward (d-going) rapidity
- Cold Nuclear Matter Effects
  - Nuclear shadowing(gluon pdf modification in target nucleus) and $c\bar{c}$ break up describes the minimum bias data well
  - Does not reproduce the centrality dependence

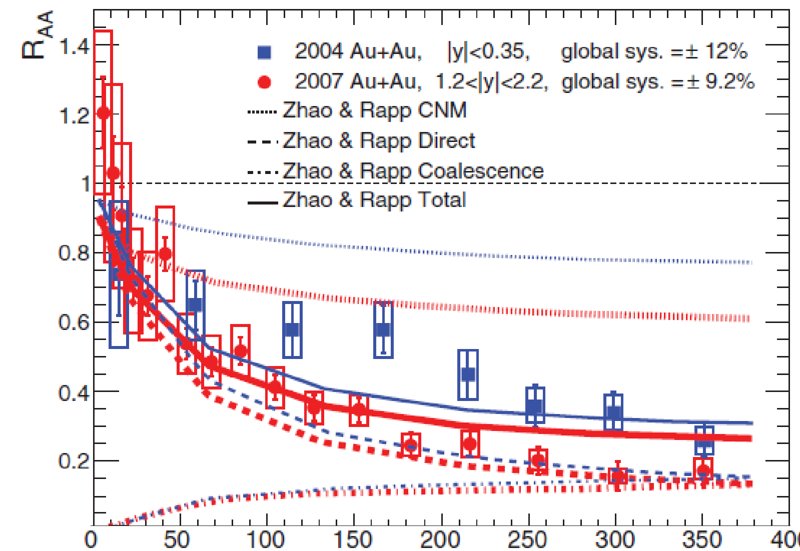


Phys. Rev. Lett. 107 (2011) 142301

Hot systems

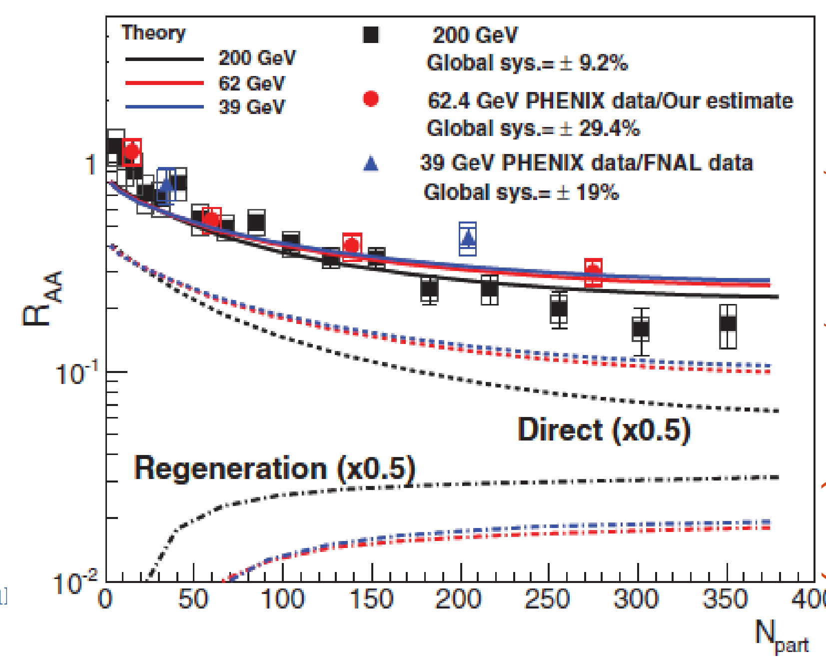
J/ψ in Au+Au

- J/ψ suppression in Au+Au at 200 GeV with respect to p+p
- Suppression increases with increasing energy density (N_{part})
- Stronger suppression at forward/backward rapidities compared to central rapidity
  - Does not increase with increased energy density as seen in N_{ch} vs η
- Very little, if any, energy dependence
- Models reproduce data well
  - Include complex admixture of effects (e.g. dissociation, coalescence, CNM effects)
  - Energy dependence: coalescence – screening balance



Phys. Rev. C84 (2011) 054912

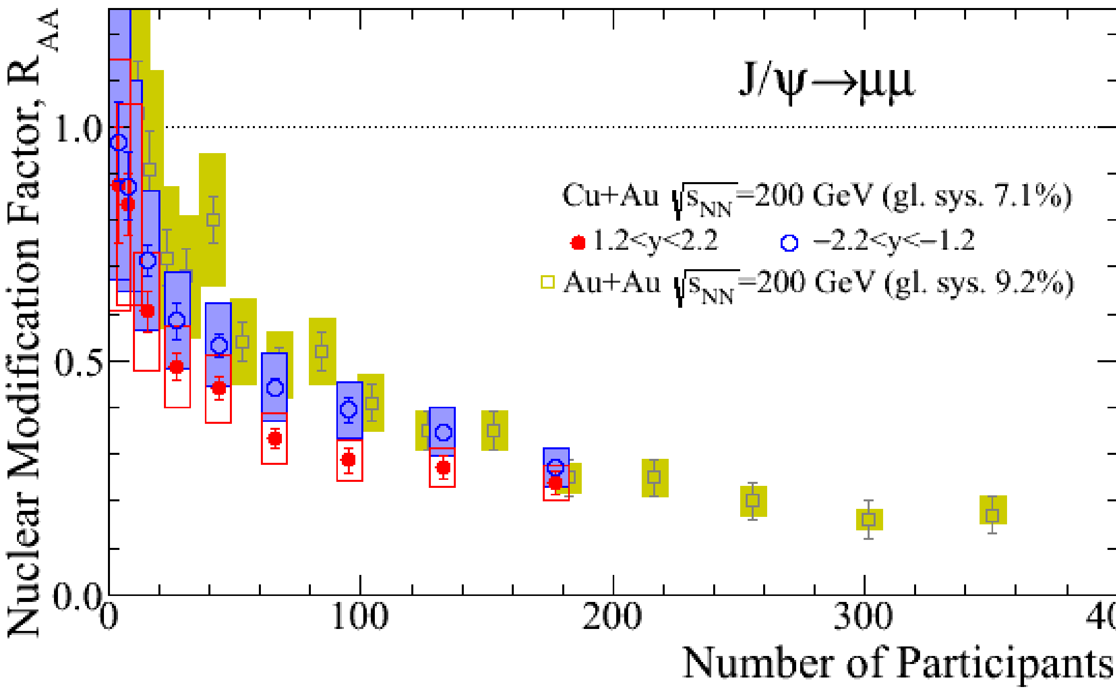
Zhao and Rapp, PRC 82,064905 (2010)



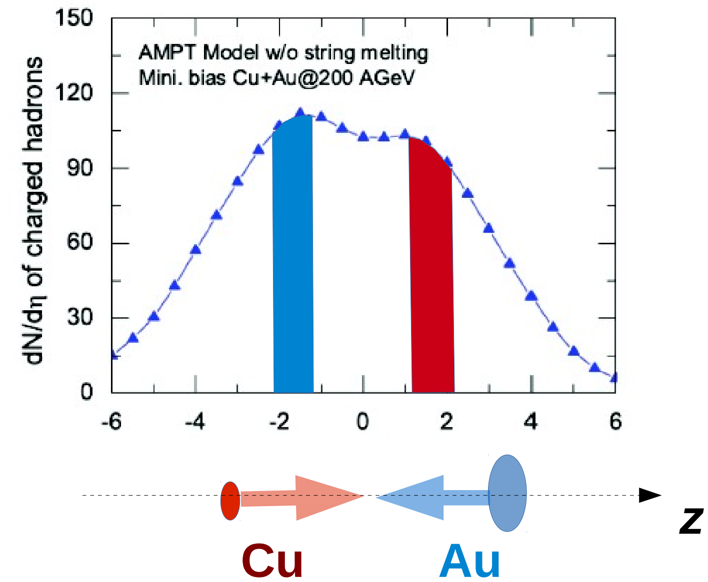
PHENIX, PRC 86, 064901 (2012)

Probing Hot/Cold

J/ψ in Cu+Au



Phys. Rev. C 90 064908 (2014)

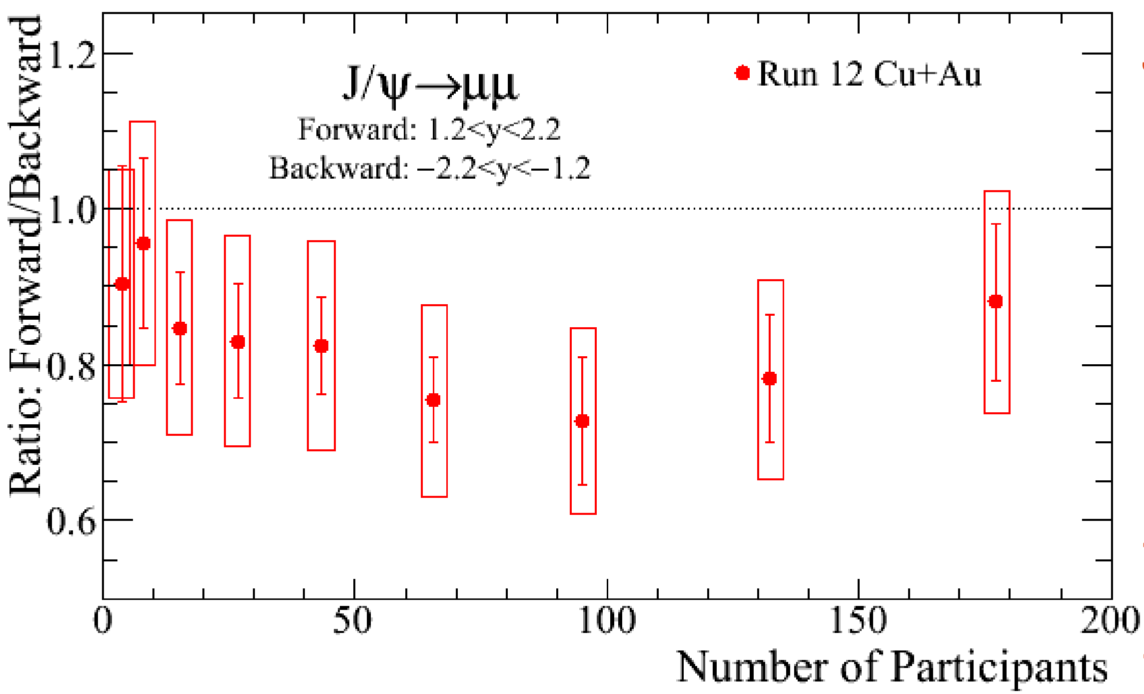


- Au-going direction
  - Similar suppression in Cu+Au compared to Au+Au
- Cu-going direction
  - More suppressed

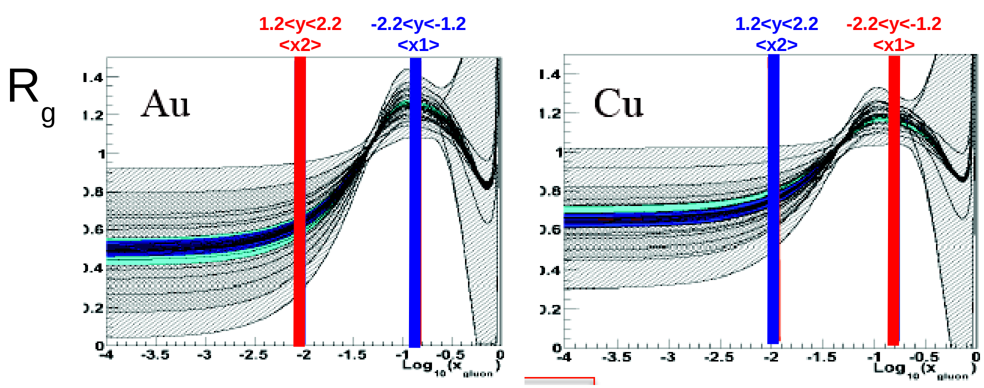
Disentangle CNM effects

J/ψ in Cu+Au

Cu-going/Au-going



Phys. Rev. C 90 064908 (2014)



Ratio ~ 20% for non-central data

CNM effects → asymmetric in rapidity

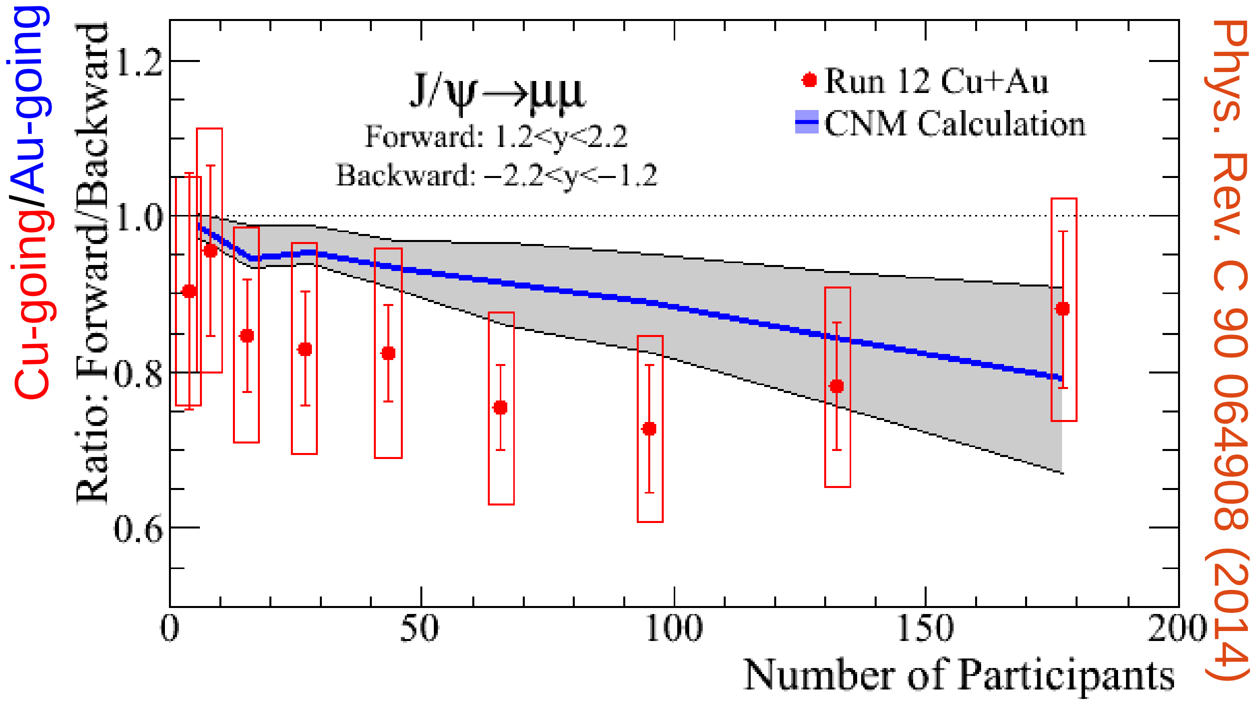
Forward CNM effects (Cu-going)

- gluon modification – J/ψ probes gluons at high-x in Cu, low -x in Au
- dynamical processes
  - J/ψ short crossing proper time in Au → probes Eloss
  - long crossing proper time in Cu → $c\bar{c}$-breakup by nucleon collisions

Backward (Au-going) → Reversed CNM effects

Disentangle CNM effects

J/ψ in Cu+Au



CNM calculation:
J.Nagle, A.Frawley, L.Levy, M.Wysocky,
PRC 84 044911 (2011)

- only includes shadowing
- Uses EPS09 nPDF and 4 mb effective cross section at all rapidities

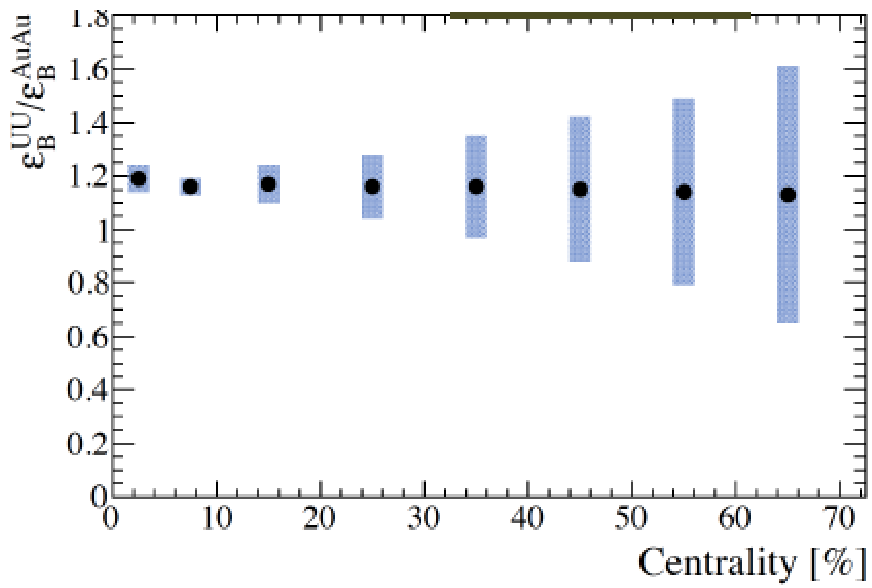
Ratio ~20% for non-central data

CNM effects → asymmetric in rapidity

- Comparison to a simple CNM calculation
  - Gives the right direction and magnitude
  - Difference due to CNM effects
  - HNM effects not included (e.g. color screening will increase the ratio)

J/ψ in U+U predictions

- The higher energy density (15-20% expected in this model)
  - should lead to stronger suppression due to color screening
- Larger N_{coll} (than in Au)
  - Should lead to increased charm by statistical coalescence



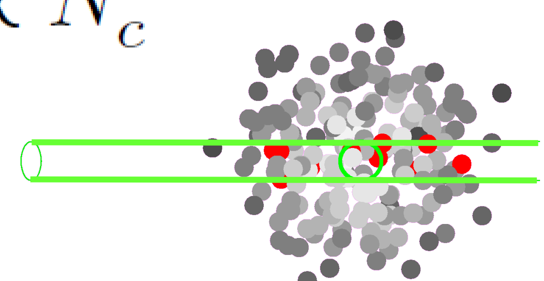
D.Kikoła, G.Odyniec, R.Vogt, PRC 84, 054907 (2011)

- Both effects in opposite direction

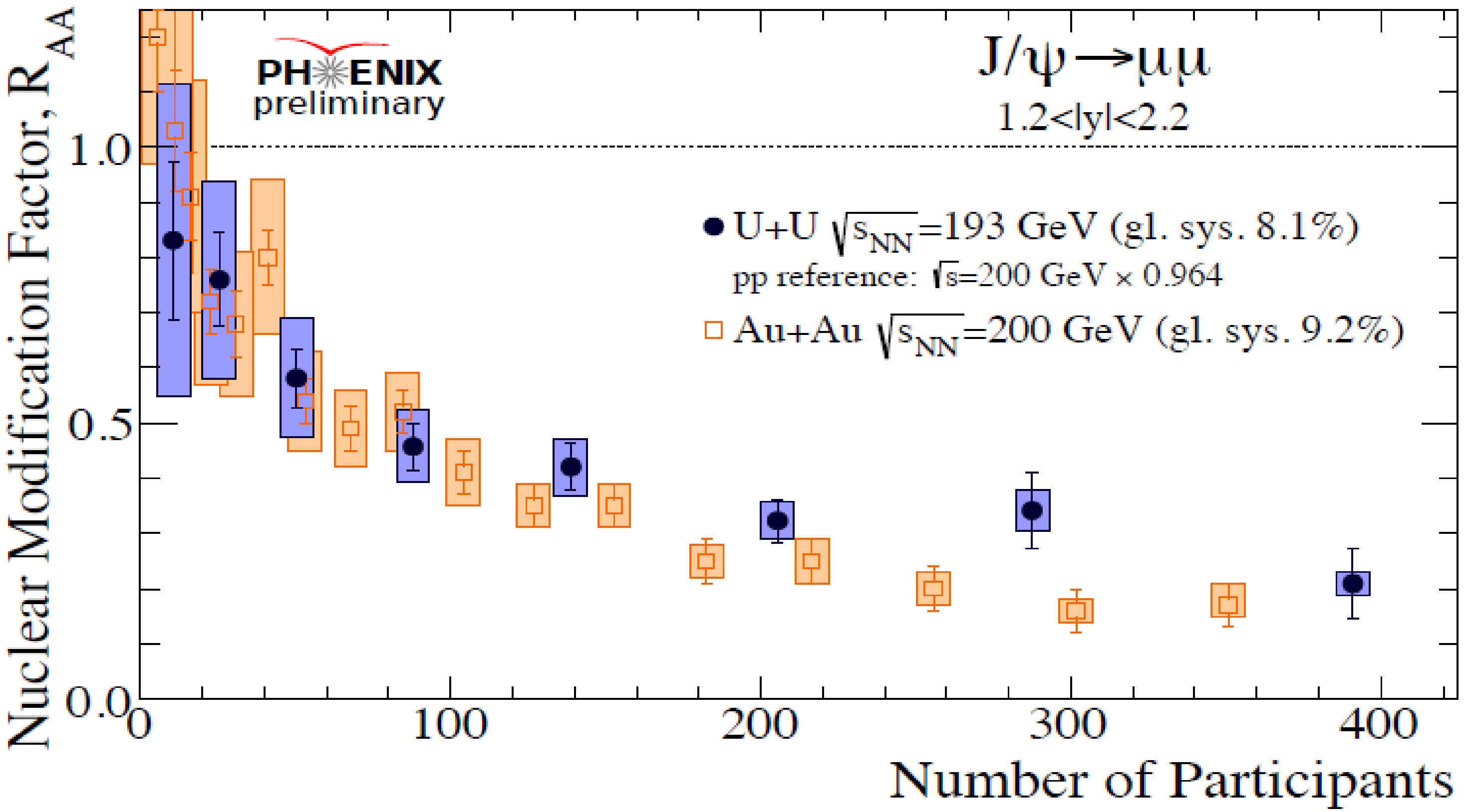
$$N_{J/\psi}^{stat} \propto N_c^2$$

- CNM: gluon shadowing is expected to be similar for U+U and Au+Au

N_{coll} – number of binary nucleon-nucleon collisions



J/ψ in U+U measurement



- Observed weaker suppression in central U+U compared to Au+Au
- Higher coalescence?

Conclusion

- Phenix has measured J/ψ production in various collision systems and center-of-mass energies

- Different collision systems
  - add variation to the initial/final state
  - allows to better control the admixture of COLD/HOT effects which modify the J/ψ production
  - can we factorize CNM effects → collective phenomena observed in d+Au
- Two latest systems
  - Cu+Au → adds variation to the initial state
    - shows significantly stronger J/ψ suppression in the Cu-going direction, consistent with the direction and magnitude expected from differences in EPS09 shadowing between Cu and Au
  - U+U → the largest system studied at RHIC
    - Shows less suppression in central data than Au+Au at the same, forward, rapidity

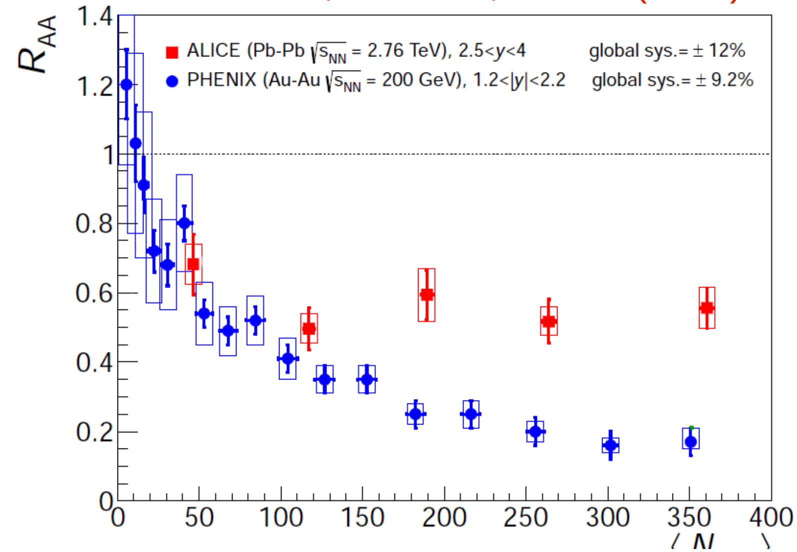
Backup

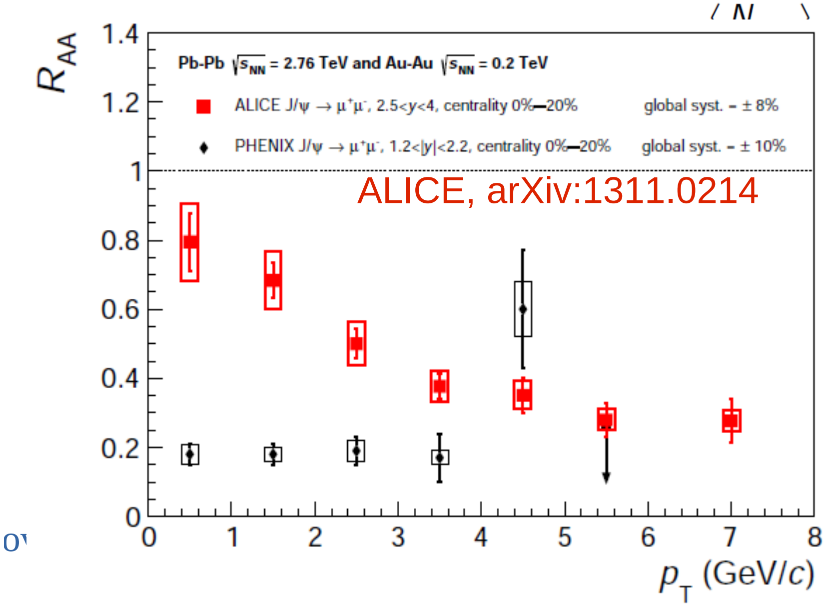
J/ψ energy dependence

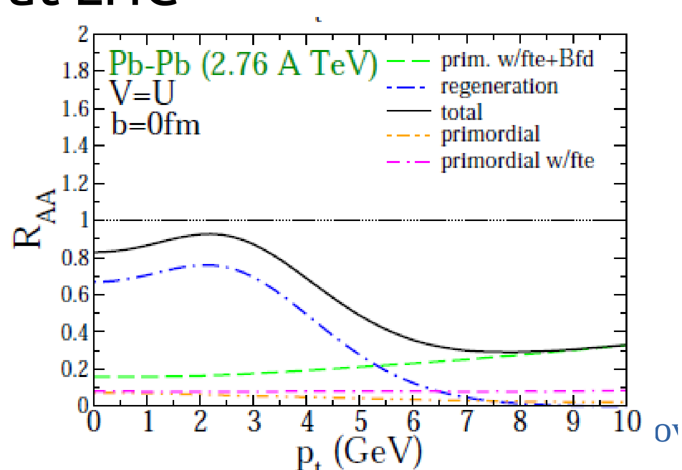
Phenix Au+Au

- At LHC
  - Suppression is much reduced
- Recombination (coalescence) important at LHC
  - Smaller R_{AA} at low p_T at RHIC energy
  - Larger v_2 at LHC

ALICE, PRL 109,072301 (2012)







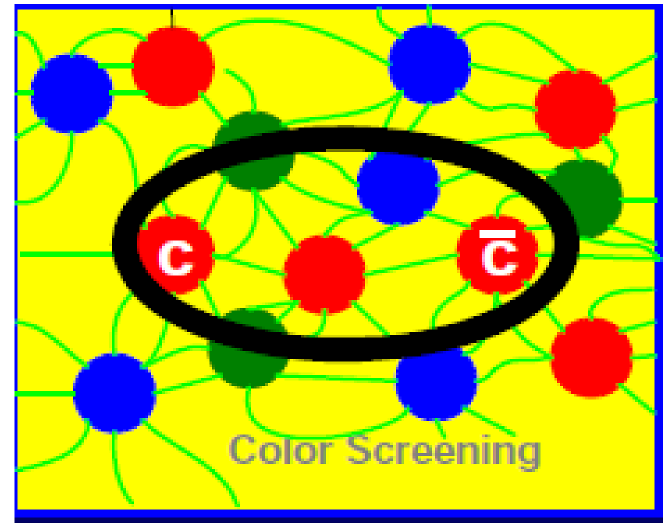
Zhao and Rapp, Nucl.Phys.A859 (2011)

Heavy quarks as a probe of QGP

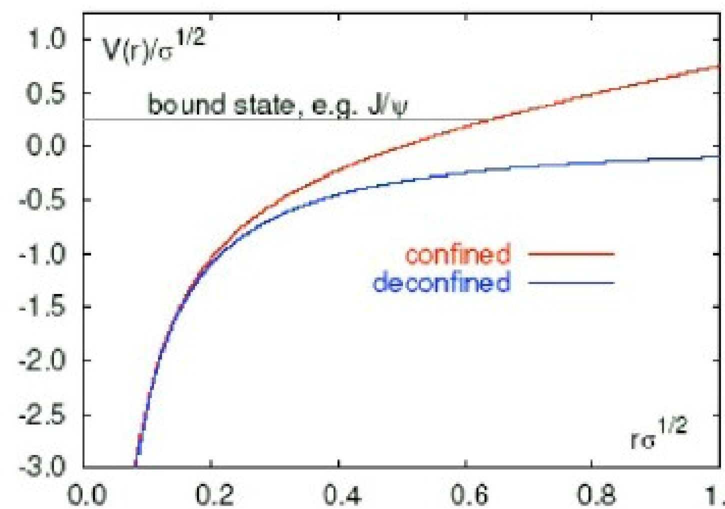
TIME?

"If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region."

- Original idea, *Matsui & Satz,1986*



- The color (Debye) screening modifies the particle potential due to the charge density of the surrounding medium
- Quarkonium potential in the medium becomes shallower
  - With increasing T different $q\bar{q}$ states "sequentially melt"
  - J/ψ becomes unbound → suppression in QGP!



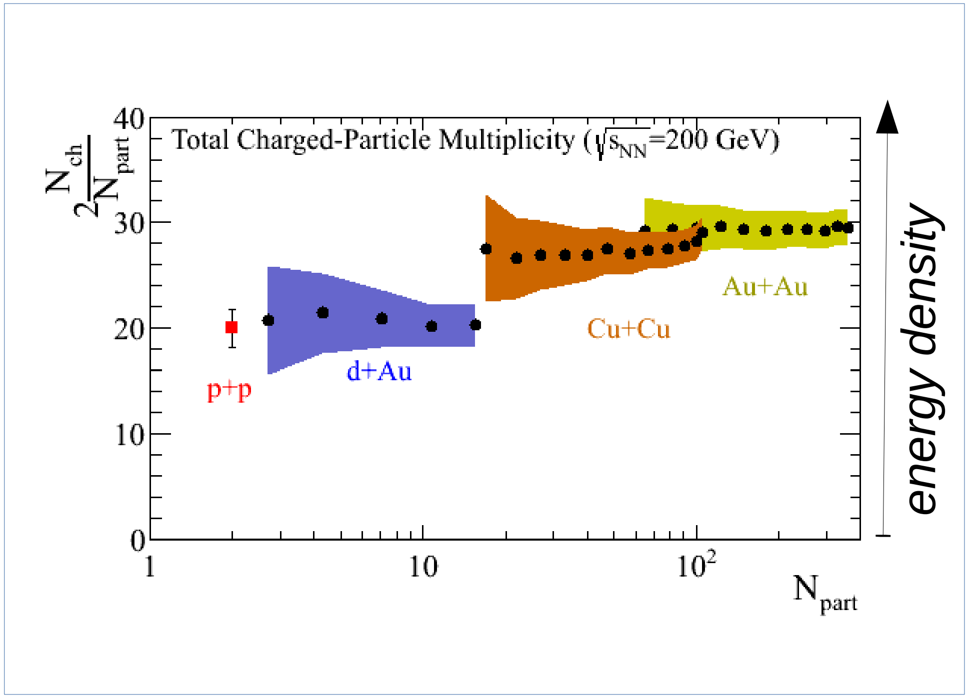
$$\boxed{V(r) = \sigma r - \frac{\alpha}{r}}$$

$$\boxed{V(r,T) \sim \frac{\sigma}{\mu}\left[1 - e^{-\mu r}\right] - \frac{\alpha}{r} e^{-\mu r}}$$

Collision system size, 200 GeV

- Reference systems
  - p+p → baseline reference
  - d+Au →nuclear/COLD reference
- Heavy-ion/HOT systems at the same center of mass energy
  - Cu+Cu → smaller system
  - Cu+Au → asymmetric system
  - **Au+Au**
  - U+U → heavy system

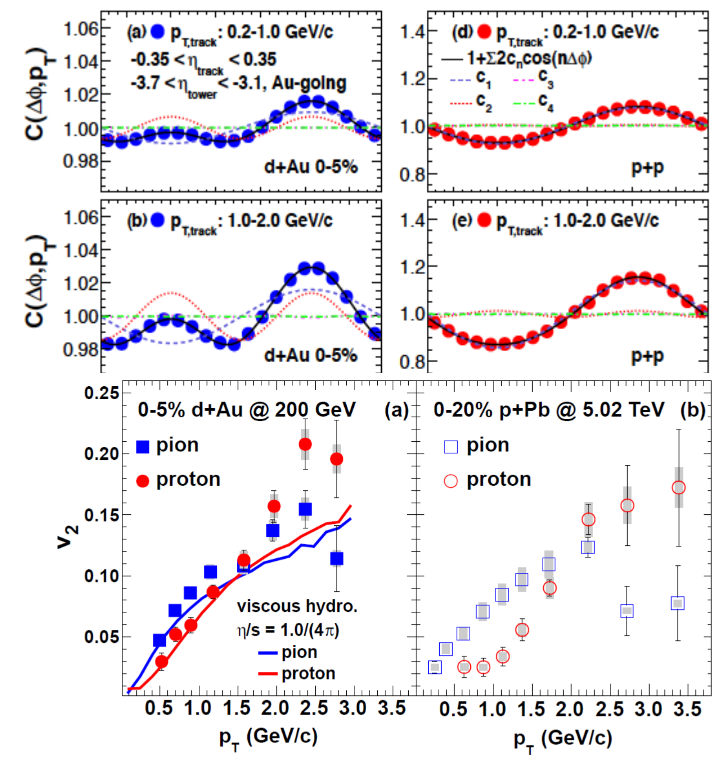
energy density



Revisited Strategy: Increase variety of collisions-systems to “control” the magnitude of physics effects

Can we factorize CNM effects?

- CNM effects
  - Complex admixture of different mechanisms
  - Strongly dependent on rapidity
- Open questions:
  - Can we factorize them?
  - Are there HNM effects in p(d)+Au?
    - Collective phenomenon seen
    - Do they affect J/ψ production?

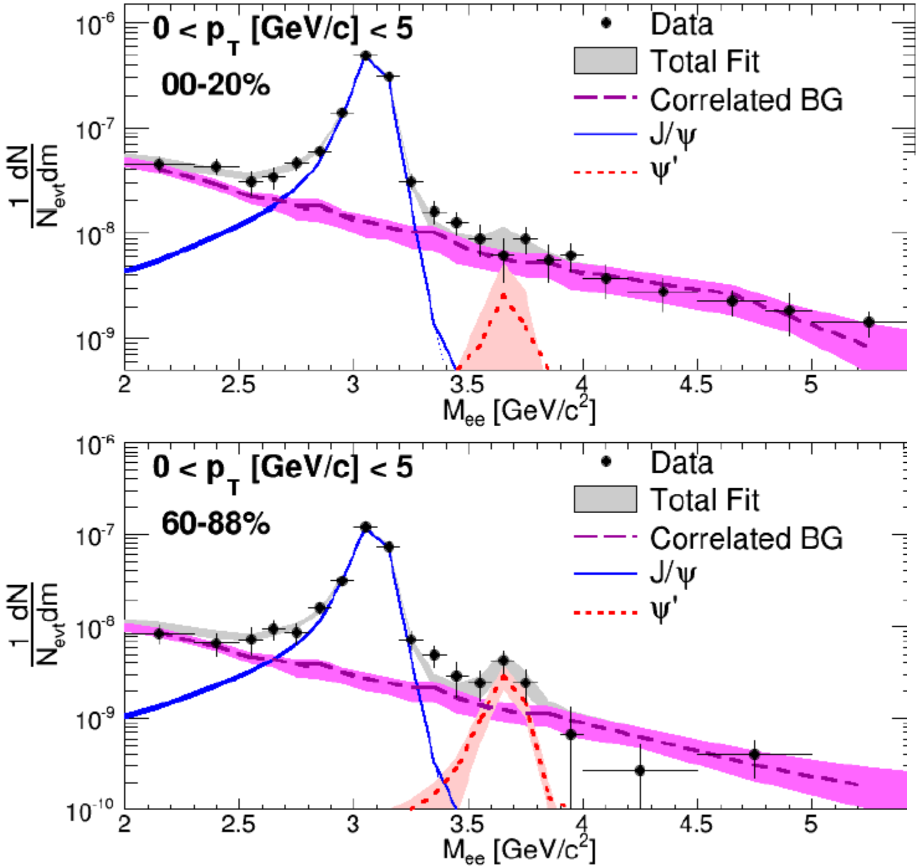


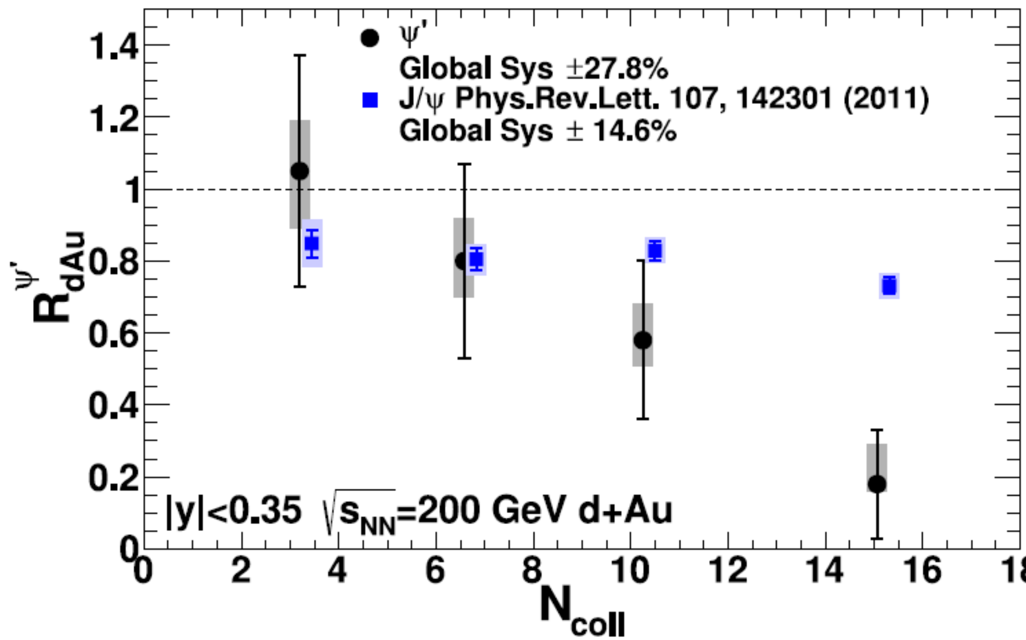
arXiv:1404.7461

Future systematic studies possible in He+Au, p+Au, and p+Al datasets

J/ψ *vs* ψ'(TIME?)

ψ'→ $e^+ + e^-$ in d+Au central arm





Phys. Rev. Lett. 111 (2013) 202301

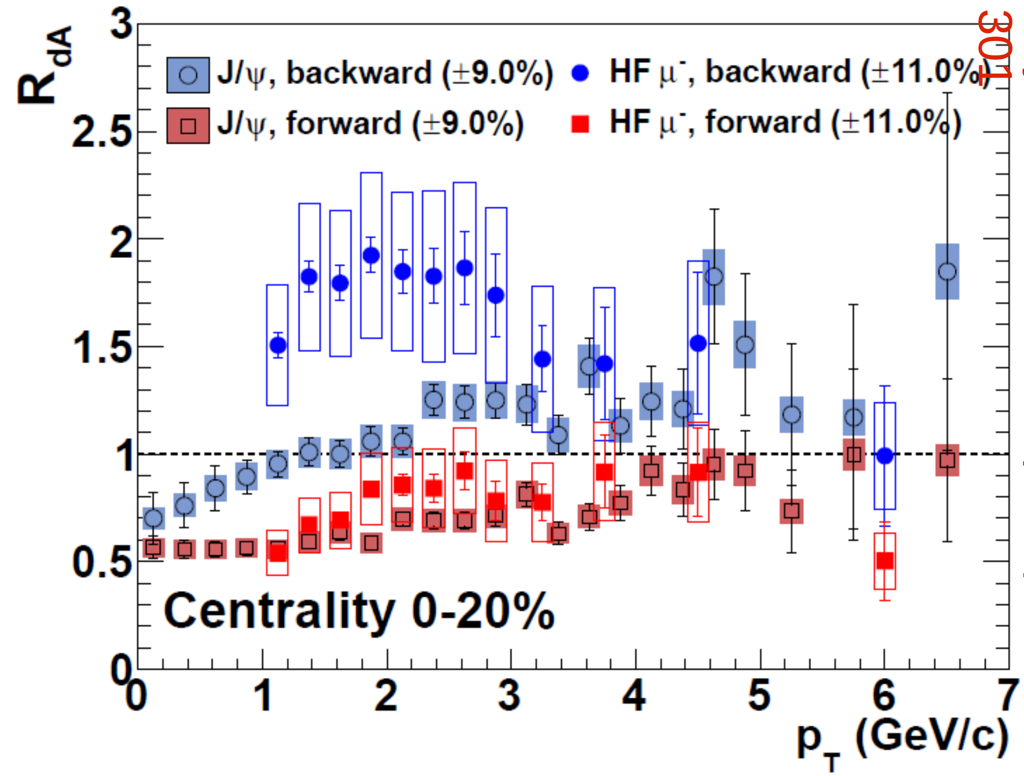
- ψ' more suppressed in central d+Au than J/ψ
- Smaller binding energy → more sensitive to final state effects

J/ψ *vs* heavy flavor(TIME?)

d+Au

- Similar modification at forward rapidity
- Distinct difference at backward rapidity
  - p_T<2.5 GeV/c
    - Dominated by charm

- J/ψ additionally sensitive to $c\bar{c}$ breakup by the nuclear matter:
  - Longer crossing time in nucleus?
  - Higher co-mover density at backward rapidity?



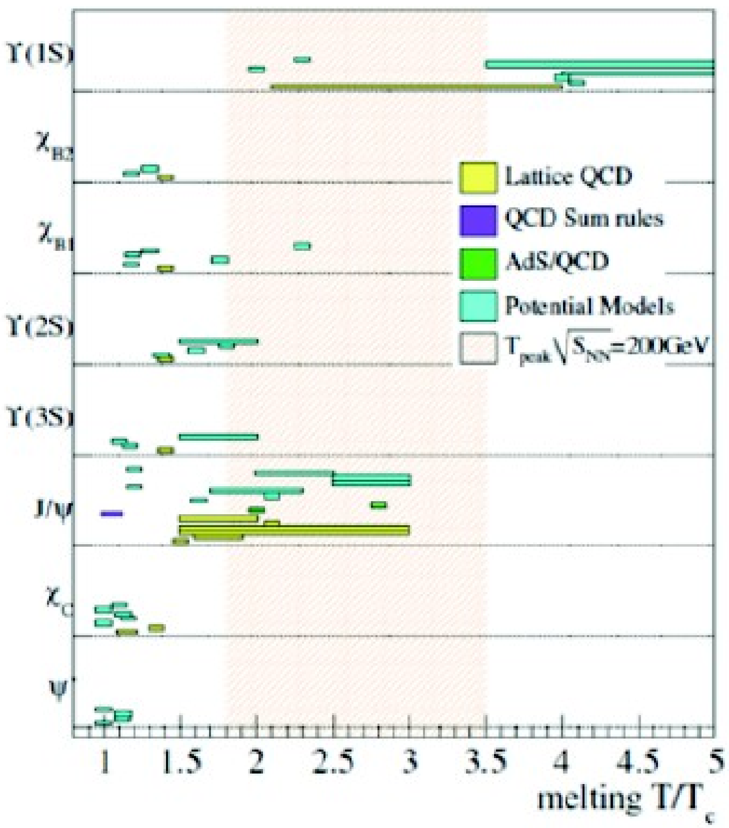
Phys. Rev. Lett. 112 (2014) 252301

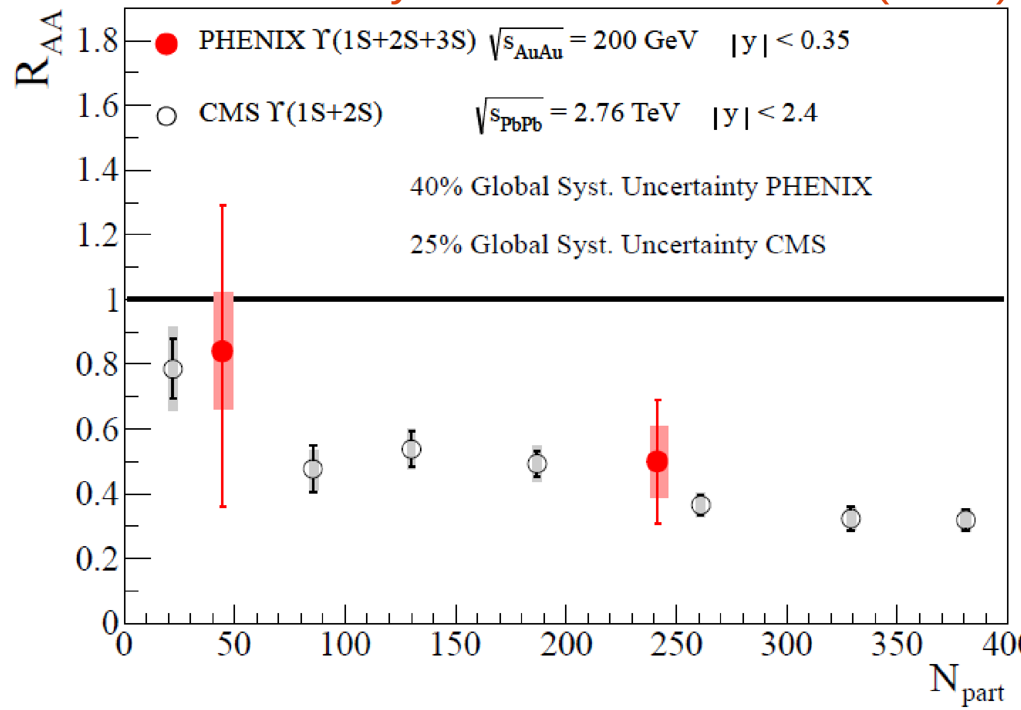
Υ family in Au+Au collisions

Phys. Rev. C. 91 024913 (2015)

"Melting Temperature"
"Color Screening"

$$R_{AA} = \frac{1}{N_{coll}} \frac{Y(AA)}{Y(pp)}$$





- Υ(1S+2S+3S) suppression in central collisions
  - Consistent with complete suppression of Υ(2S+3S)
  - Consistent with R_{AA} observed at LHC (CMS)

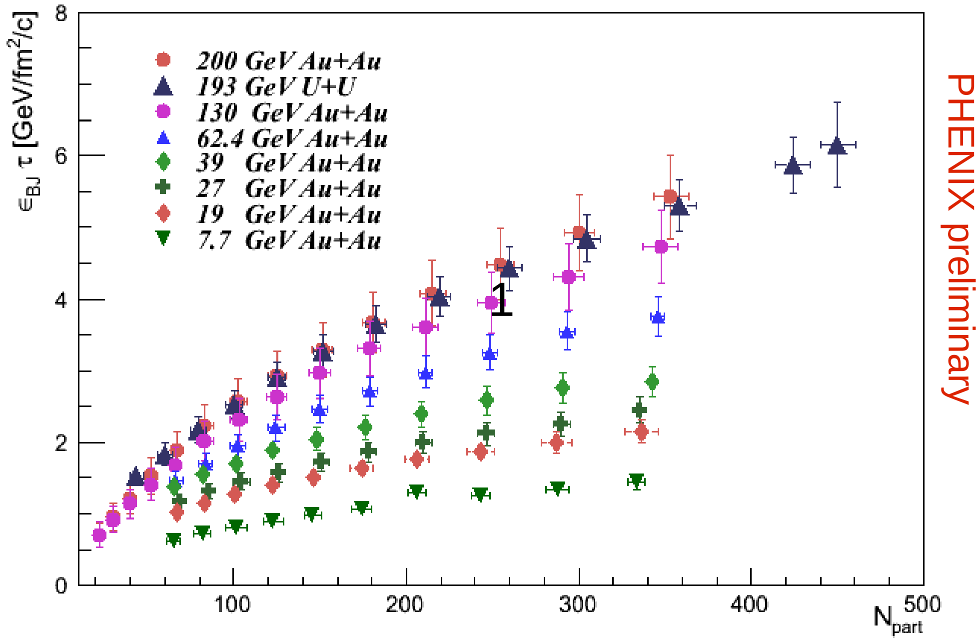
U+U: larger system

J/ψ in U+U

- New RHIC energy density record in U+U collisions

  ε_B = 6.15 GeV/fm^2/c.

- Moderate increase from central Au+Au to very central U+U (20%)
  - Some expected up to 55% for tip-tip orientation
    - PRL 94, 132301 (2005)



Upper U+U point 1% most central, all other 5% centrality bins

$$\epsilon_{\mathrm{B}} = \frac{1}{\tau S_{\perp}} \frac{d E_{\mathrm{T}}}{d y}$$

Charmonium measurements

There is now a long history of studying charmonium in A+A collisions.

$\sqrt{s_{NN}}$ (GeV)	Species	Rapidity	Experiment
17.3	Pb+Pb, In+In	$0 < y < 1$	NA50,NA60
19.4	S+U	$0 < y < 1$	NA38
64, 39	Au+Au	$-2.2 < y < -1.2$ $1.2 < y < 2.2$	PHENIX
193	U+U	$2.2 < \|y\| < 1.2$	PHENIX
200	Au+Au, Cu+Cu	$2.2 < \|y\| < 1.2$ $\|y\| < 0.5$	PHENIX
200	Cu+Au	$-2.2 < y < -1.2$ $1.2 < y < 2.2$	PHENIX
2760	Pb+Pb		ALICE